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064 In Situ Burning of Oil in Experimental Ice Leads

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IN SITU BURNING OF OIL IN EXPERIMENTAL ICE LEADS

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SUMMARY

Oil-spill cleanup in Arctic waters poses unique problems because of the presence of ice and the remoteness of potential spill sites. This work investigates the removal by burning of spilled oil in leads. Twenty-five burns of weathered Norman Wells crude were carried out under varying wind conditions in leads cut in an ice sheet. It was found that burning efficiencies of up to 90% were possible if moderate winds (similar to average Beaufort winds) herded the oil into long narrow leads. For leads of other geometries with similar winds, efficiencies might be as low as 70%. Winds of up to 4 m/s. across a narrow lead caused no oil herding and resulted in low efficiency burns. Brash ice impeded wind herding of the oil and resulted in lower burning efficiencies. Wind herded oil could be ignited at either the upwind or downwind edge with similar burning results. Weathering of oil of up to 20% did not significantly affect the burn efficiency in moderate winds.

RÉSUMÉ

Le nettoyage des fuîtes de pétrole dans les eaux arctiques posent des problèmes uniques en présence de glace et du fait de l'éloignement des sites potentiels de déversement. Dans ces travaux, nous avons essayé de brûler le pétrole deversé dans un chenal. Utilisant un pétrole brut de Norman Wells, plus ou moins altéré à l'air, nous avons conduit vingt-cinq essais de combustion dans des conditions variables de vitesse de vent et à l'intérieur de chenals découpés dans une banquise de glace. Les rendements en fraction de brut brûlée s'élevèrent jusqu'à 90% sous des vents modérés (comparables aux vents dominants en mer de Beaufort) entraînant le pétrole aux confins de chenals longs et étroits. Les rendements avec des vents similaires descendèrent jusqu'à 70% dans des géometries de chenal moins élonguées. Au-dessous de 4m/s de vitesse de vent l'entraînement du pétrole est insuffisant, même dans un chenal étroit, pour pouvoir soutenir de très hauts rendements. En outre, les morceaus de glace flotante peuvent aussi empêcher l'entraînement du pétrole, diminuant le rendement en fraction brûlée. L'allumage du pétrole entraîné par le vent peut s'effectuer aussi bien en direction aval ou amont donnant lieu à des résultats similaires. Sous des vents modérés, les rendements ne changent pas notablement pourvu que la composition en brut altéré à l'air n'excède pas 20%.

INTRODUCTION

Oil-spill cleanup in Arctic waters poses unique problems because of the total or partial coverage of ice for much of the year. If oil is lost beneath the ice surface, such as might occur with an underwater pipeline break or well blow out, the oil would collect in rough areas of the ice sheet lower surface. In regions where the spring break-up occurs, it could then percolate through the ice to form in melt pools. Otherwise, it may reach the surface where leads open up around pressure ridges, either in the multi-year ice or in transition zone ice. Because such leads may be short-lived and occur in remote areas, oil cleanup would be very difficult under the best circumstances.

The transport and disposal of collected oil and debris in the Arctic is a problem of similar scope to that of containment and pick-up. Hence, the burning of spilled oil in situ appears be a simple and straight forward alternative. Several recent studies have addressed various aspects of in situ burning. Buist and Dickens (1981) reported on a field study of oil cleanup in ice-infested waters conducted under the auspices of The Canadian Offshore Oil Spill Research Association (COOSRA), in which the burning of oil in melt pools was studied. A field trial which studied oil movement and burning in pack ice was carried out by Buist and Bjerkelund (1986). The OHMSETT facility (the U.S. Environmental Protection Agency's Oil and Hazardous Materials Simulated Environmental Test Tank in New Jersey) has been used to determine burning rates and burning efficiencies of oil in broken ice with varying ice coverages (Smith and Diaz (1985)). Energetex Engineering (1977) studied spreading rates of oil on water and the effects of wind herding. Buist and Twardus (1984) conducted theoretical and laboratory studies on oil and flame spreading under differing wind conditions. To date, the one area of burning as a cleanup technique in ice-infested waters that has not been adequately addressed is that of burning oil in ice leads.

In order to evaluate the parameters of burning which are likely to be critical in ice leads, a series of experiments was carried out in February 1986 at the Esso Resources ice test basin in Calgary, Alberta. The tests were designed to evaluate the effects of wind herding, oil weathering, oil thickness, lead geometry, and the presence of brash ice on burning efficiency. The size of the facility allowed burning experiments to be carried out at essentially full scale.

TEST FACILITIES AND EQUIPMENT

The Esso ice test basin is a large outdoor concrete pool 30 m wide by 56 m long and varying in depth from 0.75 m to 3 m. Water capacity is approximately 2200 m^3. Two, 200,000 BTU/h, refrigeration units are available for forming the ice sheet.

A device was designed and constructed to measure the thickness of oil on water. It consists of a hollow aluminum bar 5 cm by 12 cm in cross-section and 1.5 m long, with leveling feet at each end. A sliding trolley, which runs along the beam but is electrically isolated from it by teflon bearings, holds a digital readout micrometer screw. One lead of a sensitive ohmmeter is attached to the micrometer screw while the other lead is grounded to a large paddle which extends from the aluminum bar into the water below the oil slick. The device detects the oil-water interface by measuring the change in resistivity as the micrometer screw is turned vertically through the oil to the water. In laboratory tests, the reproducibility of oil thickness measurements with the device was ±0.03 mm. Under the best lighting conditions, the device always detected the oil-water interface before the screw tip was visible below the oil.

Heat fluxes into the water and ice from the burning process were measured with an underwater rack which held six thermocouples and six thermistors. Each thermal sensor could be raised or lowered to a preset depth or imbedded in the ice at the side of the lead. The sensor outputs were connected through a sheathed cable buried in the ice to a Sea Data Inc. Model 1250 logger. The signals were digitized at a one-second rate and recorded on magnetic tape for later analysis.

Winds of selected speeds were generated by varying the propeller speeds of a 17 ft airboat. It consisted of a 150 hp aluminum, V6 engine driving a 54 inch propeller and mounted on an aluminum hull. The entire unit was light enough to be easily moved across the ice surface. Winds could be controlled to within ±0.5 m/s of the desired velocity provided that local winds were calm. This was ensured by erecting fences made of 4 ft by 8 ft plywood panels, parallel to the ice leads and 1.5 m from each lead edge. A hand-held anemometer was used to measure the air flow speed 20 cm above the water surface.

Each burn was recorded on colour video with a portable Sony camera mounted on a tripod. An infrared video tape from a Barr and Stroud model IR18 thermal imager was made for some of the burns.

METHODS

During the winter of 1985-86, the ice sheet of the outdoor basin froze naturally to an average thickness of 45 cm. Chain saws were used to cut several artificial leads in the ice. For most experiments the leads were 1 m wide by [illegible] m long, but a semicircular hole 5 m in diameter and a square hole of 5 m sides were also cut. In addition, two short leads 1 m wide by 2 m long with triangular extensions of 1 m base and 4 m perpendicular were cut. Typically, the water surface was 3 cm to 4 cm below the top ice surface.

After the lead was cleared of brash ice, the temperature sensing array was lowered into the lead and the sensing elements adjusted for correct heights. Aged Norman Wells crude (from 10 L to 40 L) was then poured carefully on the lead surface and allowed to spread under the experimental wind conditions selected. After approximately 15 min, oil spreading ceased and thickness measurements could be made using the device described previously. A sketch of the oil extent on the lead was made. The wind speed was adjusted as required by varying the airboat engine speed. Wind speed was always measured with the portable anemometer held at the upwind edge of the oil slick.

Norman Wells crude was aged by parging the oil in barrels with a stream of compressed air. Weathering (topping) was estimated both from the loss of oil from the barrel and from simulated distillation gas chromatography (SDGC). These estimates were confirmed with viscosity and specific gravity measurements on the parged oil.

In two experiments the oil was allowed to weather on the water surface by approximately 10% (measured by SDGC). Ice, which had formed under the oil during the weathering, was broken into pieces of 2 cm per edge or less and mixed thoroughly with the oil before ignition.

Oil was ignited with a small hand-held torch, usually at the upwind edge of the slick but occasionally at the down-wind edge (Test 19, for example). The progression of the flame front was then measured with a stopwatch as it passed metre marks at the edge of the lead. When burns took place in irregular leads, a sketch of the burning front at regular intervals was made and later checked for accuracy by viewing the video tapes. Notes on the ease of ignition, the general weather conditions, and any unusual burning phenomena were made during the burn.

After completion of a burn, the viscous residue was removed from the lead using sieve shovels and was placed in plastic bags. Care was taken to remove any entrained water

before the residue was weighed and then stored for later analysis. Residue recovery was estimated to be better than 95%. Samples of lead water were taken for hydrocarbon analysis both before and after the burn.

RESULTS AND DISCUSSION

Some of the results of the burning experiments are summarized in Table 1. The range of parameters studied and comments concerning these can be found in Table 3. Primary measurements of oil weathering, wind speed, burn time, amount of oil spilled, and residue volume were used to calculate the flame spreading rate, the burning regression rate, and the burning efficiency. The residues have been characterised by viscosity, specific gravity, and gas chromatographic analyses. The dichloromethane extractable hydrocarbon content of the lead waters has been measured. Each will be discussed below.

GENERAL OBSERVATIONS

The burns followed a typical sequence after ignition at the upwind edge of the slick. Initially, the fire spread slowly with small, blue flames at the base of 10 - 15 cm yellow flames. As sufficient heat was generated to volatilize heavier components, the flames increased in size and spread more rapidly. About one minute after ignition the fire usually encompassed 1 m^2 of the slick with flames approximately 1 m high. At this point rapid boiling of the lead water would commence, accompanied by popping noises, voluminous black smoke, and a marked increase in the flame size. In the rectangular leads, the flame front progressed along the lead at a uniform rate. Initial fuel type did not appear to have any effect on the fire at this mature stage. Frequently, a fire storm, which behaved like a small tornado, would develop. In the square and circular leads where the oil was unconstrained, the burning pattern was less regular. Often the flame would initially advance over a slick area as the oil warmed, then retreat due perhaps to small wind changes, and advance again later as oil was herded toward the flame. Occasionally, patches of oil were never ignited. In all leads as the fuel was exhausted, the fire would rapidly die down except for a few scattered blue flames which might persist for a minute or so before extinquishing. Rapid cooling of the residue followed.

WIND HERDING

Energetex Engineering (1977) has shown that low winds can herd non-ignitable sheens of oil to sufficient thicknesses for burning. They determined that fresh slicks had to be thicker than 0.6 mm to burn and heavily weathered oil had to be at least 3 mm thick to burn. In this study, the oil was weathered from approximately 5% to 20% and consequently, the slicks used were from 1.0 to 4.0 mm thick to ensure ignition.

TABLE 1
RESULTS OF BURNING EXPERIMENTS

Oil Weathering (%)	Test #/Conditions	Volume Spilled (ℓ)	Wind Speed m/s	Burn Time After Ignition(s)	Residue Volume (ℓ)	Burn Efficiency (%)	Herded Slick Area (m^2)	Regression Burning Rate (mm/min)	Flame Velocity (m/s)
5	10	30	--	271	3.2	89	9.6	0.6	0.05
	13	20	1	189	4.7	77	7.3	0.6	0.12
	15	30	2.5	290	4.1	86	7.8	0.7	0.15
10	4	30	1.5	158	3.8	87	5.7	1.7	0.05
	5	30	--	358	4.5	85	8.1	0.5	0.04
	6	20	--	199	5.8	71	9.0	0.4	0.07
	7	40	--	375	6.5	84	10.0	0.5	0.03
	8	10	--	356	3.3	67	3.7	0.3	0.03
	9	30	2.5	226	3.1	90	3.2	2.2	0.07
15	16	30	--	303	4.4	85	9.5	0.5	0.05
	20	30	0.5	346	2.5	92	4.0	1.2	0.03
	17	30	2.5	195	3.0	90	3.0	2.7	0.08
20	23	30	--	277	5.7	81	7.4	0.7	0.04
	21	30	1.4	201	4.9	84	4.5	1.6	0.03
	25	30	5.8	225	4.7	84	1.6	4.1	0.07
~ 10	2 Brash	27	--	885	8.2	70	9.0	0.1	0.01
~ 10	3 Ice	27	4.5	565	5.4	80	5.0	0.4	0.03
5	24 Circle	20	3	189	5.4	73	3.5	2.1	--
	22 Crosswind	30	4	305	6.6	78	9.8	0.2	--
	11 Square Centre	30	--	161	9.1	70	12.6	0.5	--
	12 Square Side	30	3	414	7.5	75	5.5	0.6	--
	14 Square Corner	30	3.5	467	7.9	74	5.5	0.5	--
15	18 Triangle Upwind edge ignition	20	2	174	2.3	89	2.7	2.2	0.11
	19 Triangle Downwind edge ignition	20	2	574	2.6	87	2.7	0.7	0.01

In the Beaufort, winds average 3 - 5 m/s. Because of the ground wind shear over level ice, these meteorologic measurements recorded at 10 m height, relate to winds of approximately 2.5 m/s at ground level (Dome (1981). The experiments reported here were carried out with ground winds of 0 - 5.8 m/s.

During several of the tests with steady winds, it was possible to measure the oil thickness profiles along the length of the lead. Figure 1 shows these profiles measured during five of the tests. As the oil becomes more viscous, it is herded to greater thicknesses. Energetex Engineering (1977) quote a relationship derived by Hoult for the thickness of a slick wind-herded against a barrier, as follows:

$$d^3 = \frac{2V}{W}\left(\frac{\rho_A}{\rho_W}\right)\frac{C_f U^2}{g\Delta}$$

where $\Delta = (\rho_W - \rho_O)/\rho_O$

d = thickness of oil at the barrier
ρ = densities of air, oil, and water
V = volume of oil spilled
W = barrier width
U = wind velocity
g = acceleration of gravity

and C_f is the skin friction coefficient for a flat plate of length L.

$$C_f = 0.072\left(\frac{\nu}{UL}\right)^{1/5}$$

where ν = kinematic viscosity.

The kinematic viscosity was measured to be 30.3 cs at 0 C for 10% weathered oil and 56.7 cs for 15% weathered oil. Thicknesses calculated from the expression were compared to the measured thicknesses (see Figure 1) at the 10 m mark of the lead with the following results:

Test Conditions		Measured	Calculated
% weathered	wind (m/s)	(mm)	(mm)
10	1.5	6.2	8.9
	2.5	7.6	12.5
15	0.3 (low)	4.5	4.1
	0.5	6.4	5.0
	2.5	9.8	13.4

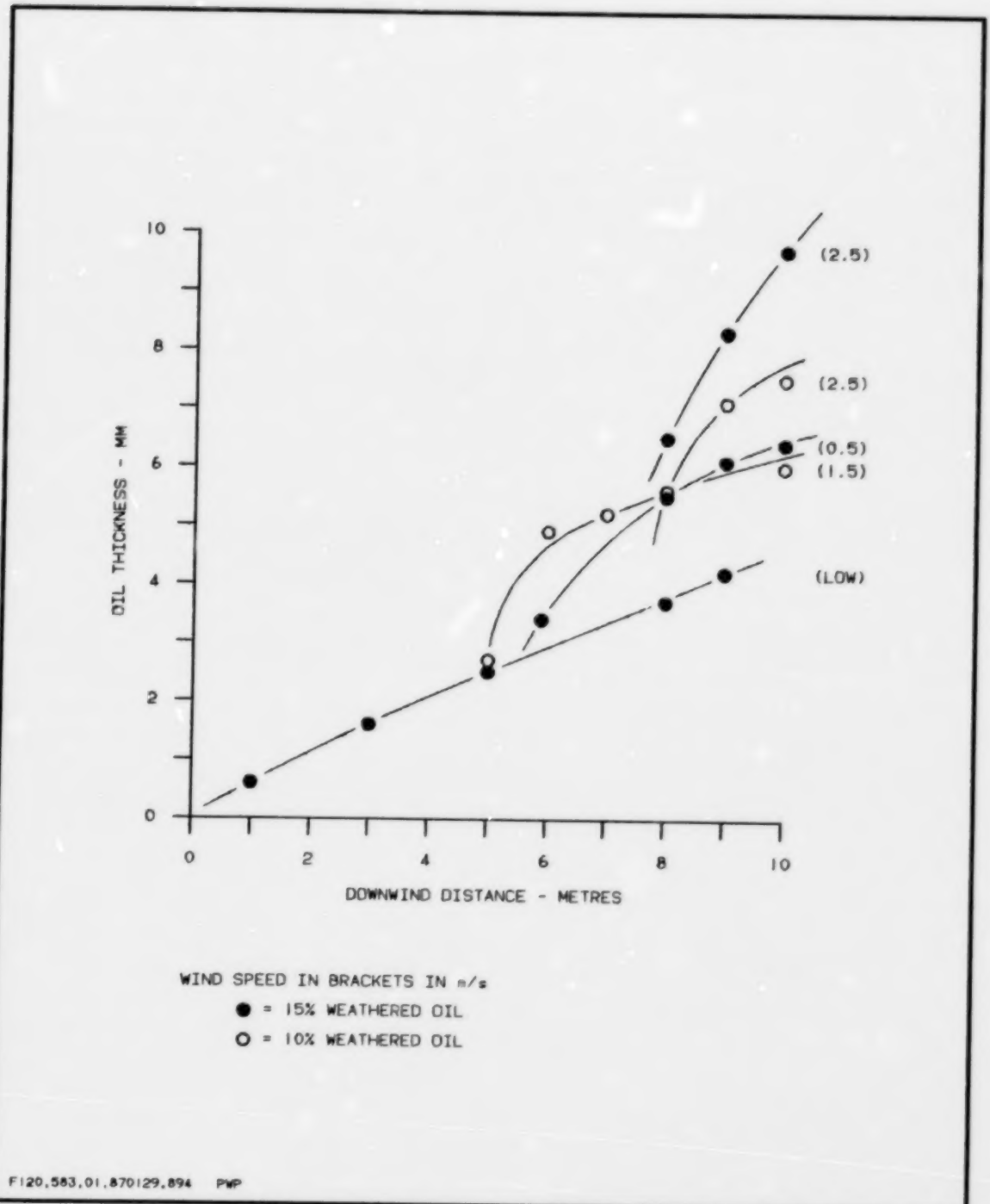

FIGURE 1. OIL THICKNESS PROFILE

Except were winds were low (and difficult to measure) Hoult's expression yields thicknesses which are about 40% higher than those measured.

FLAME SPREADING RATE

In Table 1 the average flame spreading rate (flame velocity) is shown, measured between the time the flames covered the first square metre of the slick and the time the flame front reached the end of the lead. No measurements were made for the square or circular leads. The results for flame spreading in rectangular leads with oil thicknesses of 3 mm are plotted in Figure 2(a). There is a general increase in flame spreading rate with increasing wind speed and a dependence on degree of oil weathering. However, neither is marked once the weathering exceeds 10%. Possibly the flame spreading rate depends on the amount of light hydrocarbons in the oil available to preheat and vaporize the remaining material, and most of these have been lost after 10% weathering.

The presence of brash ice significantly slows the flame front (compare the rates of Test 3 to Test 9 in Table 1). From Figure 2(b) it appears that the amount of oil spilled, once it is thicker than 3 mm (in this work, 30 ℓ spilled), does not affect the flame velocity. The graph suggests that a 2-mm thickness is optimum but more tests are needed to confirm this finding.

These results are in general agreement with the work of Buist and Twardus (1984). Their results from wind tunnel experiments using Alberta Sweet Mixed Blend crude oil show a linear relationship of flame velocity with wind speed and a dependence on oil aging. For 8-hour (approximately 10%) aged crude they measured the flame velocity to be 0.05 m/s at a wind speed of 1.5 m/s and about 0.07 m/s for a wind speed of 2.5 m/s in good agreement with our experiments (see Tests 4 and 9).

REGRESSION BURNING RATES

Average regression burning rates were calculated from the wind herded areas of the oil before ignition and the total burning times after the fire had become established. The rates are listed in Table 1, and are plotted in Figure 3, for 3 mm oil thicknesses in rectangular leads. For a given oil type there is a linear relationship between the wind velocity and the regression burning rate. This result may be due to the herding which thickens the oil and promotes more efficient transfer of heat from the flame to

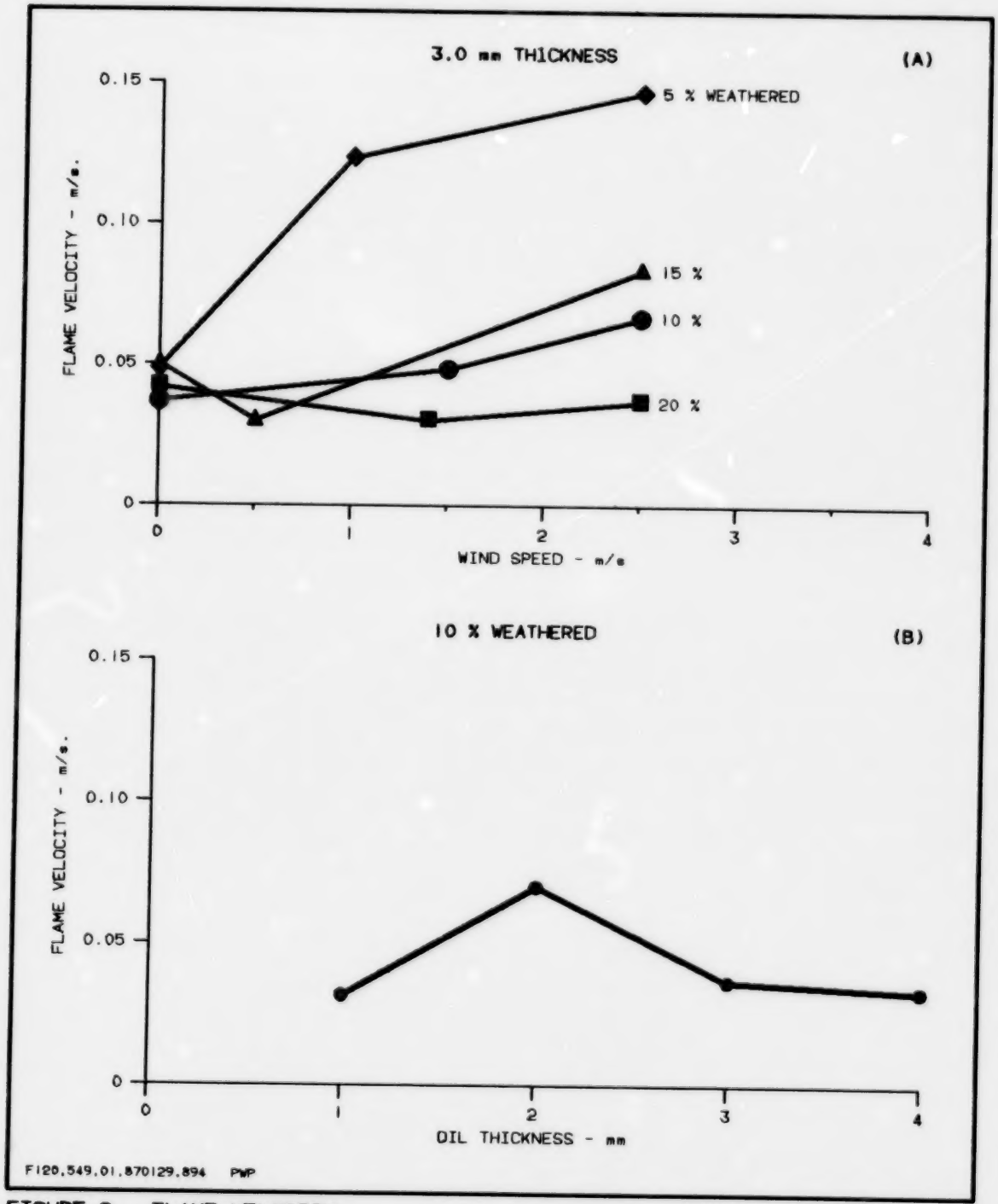

FIGURE 2. FLAME VELOCITY

volatilize the remaining fuel. In addition, the wind ensures that the fire is not oxygen limited. Figure 3 shows that the more weathered oil burns at a faster rate probably because more viscous oil is wind herded to greater depths. Experiments 2 and 3 (Table 1) show that brash ice, which should impede the heat transfer, dramatically decreases the burning rate.

The effect of lead geometry is not quite as apparent. Where wind herding can confine the oil such as in the apex of a triangle (Test 18) or along the circumference of a small circle (Test 24), the burning rates are similar to those in the long rectangular leads. Unconfined slicks such as along the side of a large square lead (Test 12) or in the centre of an open area (Test 11) have lower burning rates.

No exactly comparable measurements exist in the literature but Buist and Twardus (1984) have measured the regression rates of fresh Alberta Sweet Mixed Blend crude under calm, confined conditions and find that the rates vary from about 1.0 to 2.0 mm/min for oil thicknesses of 4 - 40 mm. In small-scale laboratory tests, Smith and Diaz (1985) report burn rates of 0.2 - 0.4 mm/min. for 2.5 to 10.5 mm thick fresh Prudhoe Bay crude oil.

BURNING EFFICIENCIES

In Figure 4(a) the calculated burn efficiencies as a function of wind speed and oil weathering are plotted for 3 mm deep oil in rectangular leads. Wind appears to improve the efficiency slighty. There does not appear to be a consistent dependence on oil weathering, except under calm conditions (Figure 4(b)). Figure 4(c) shows that the efficiency increases with the amount of oil burned, at least to a depth of 4 mm.

The efficiencies for other tests listed in Table 1 show that the lead geometry is important for good burning. Where the oil can be confined by wind herding (such as at the apex of a triangle as in Tests 18 and 19) the efficiencies are comparable to those in straight leads and independent of where the oil was ignited. For more open leads where the oil is herded along a straight edge, the efficiencies are 10% to 20% lower (Tests 11, 12, 14, and 24). In Test 22 the wind was directed across the width of a 1 m by 10 m lead where the ice height above the water was 3 cm. At low winds no herding was observed. Eventually, the wind was increased to 4 m/s before ignition, still without any observed herding.

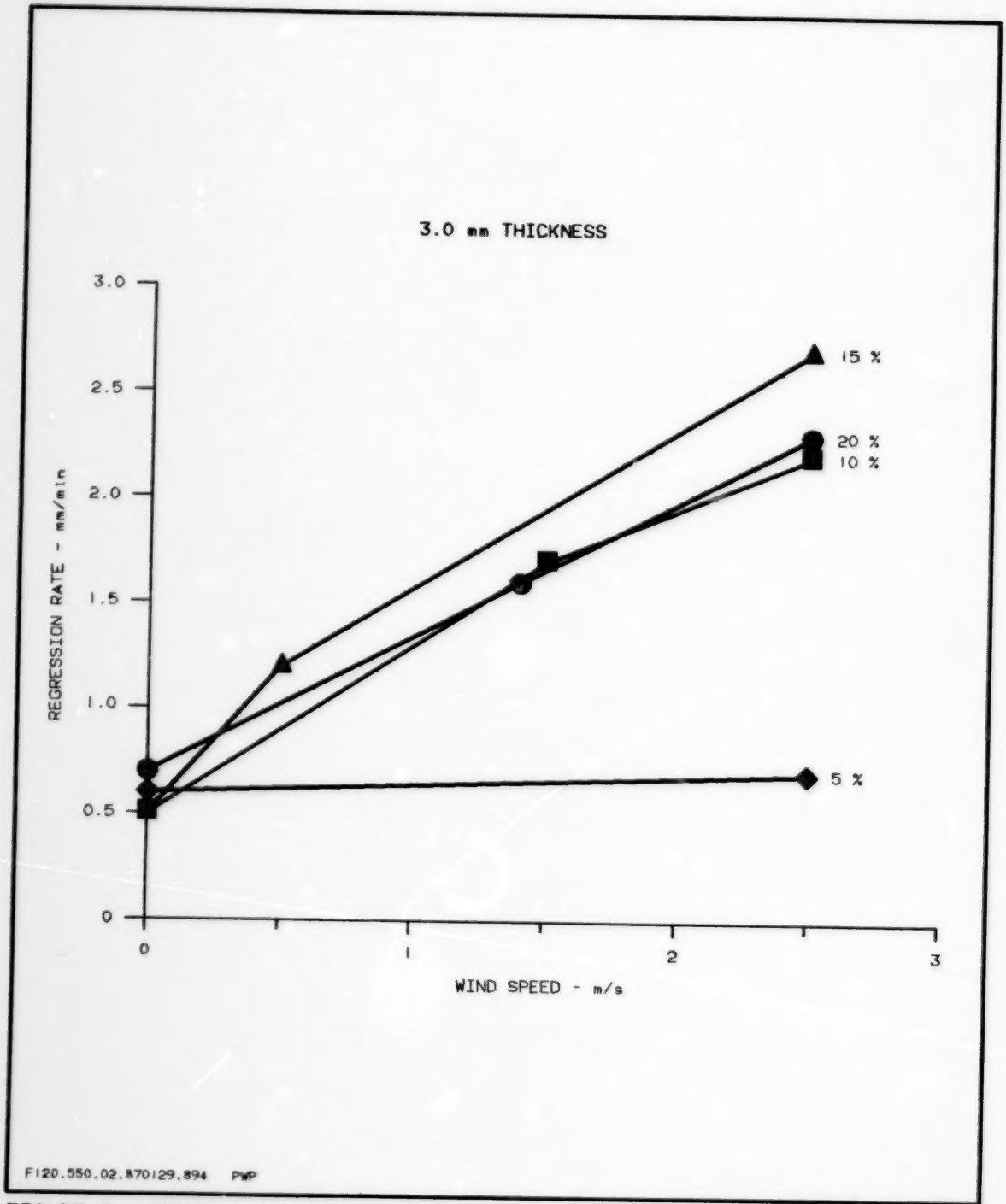

FIGURE 3. REGRESSION BURNING RATE

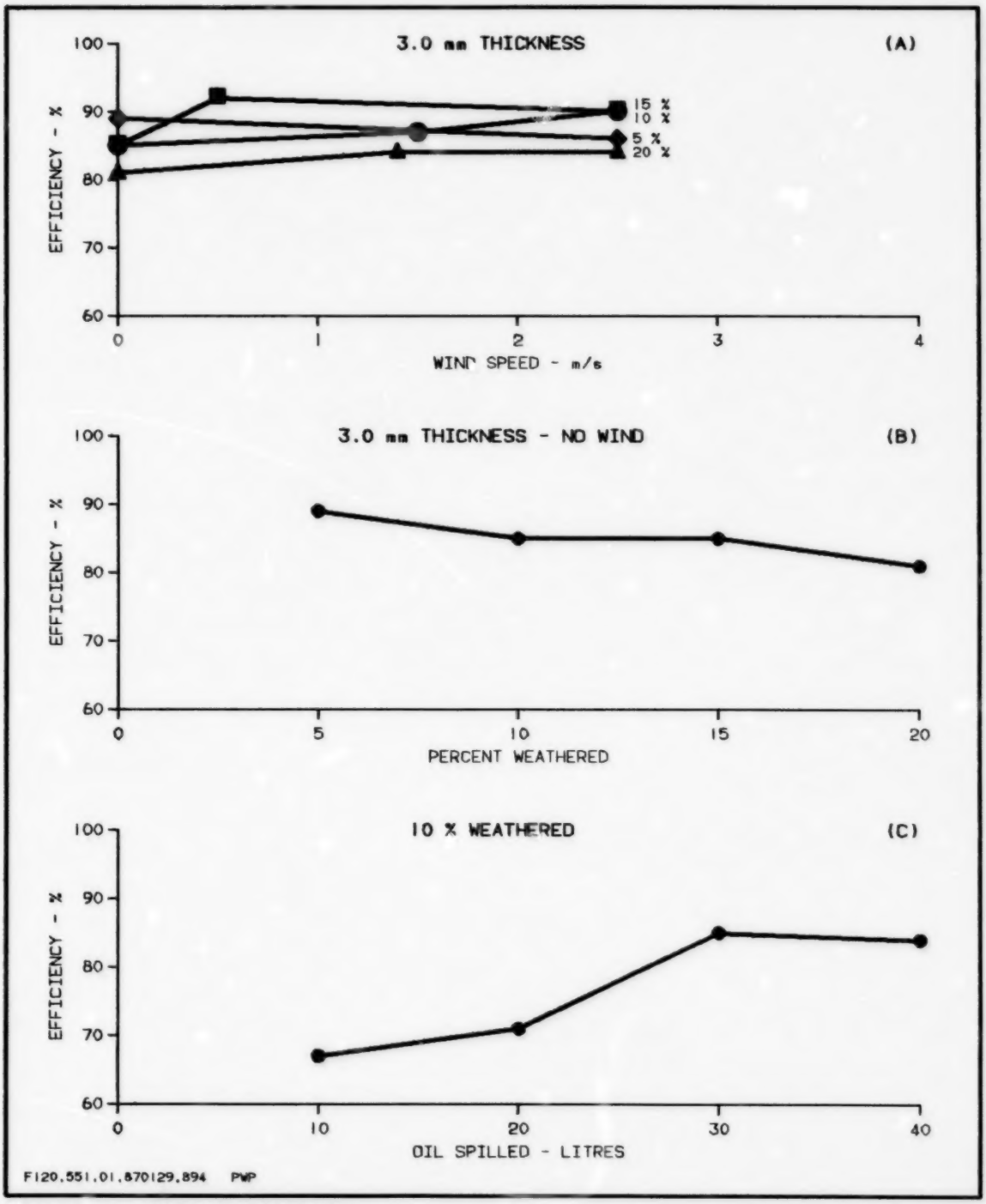

FIGURE 4. BURN EFFICIENCY

There appears to be a relationship between the speed of oil consumption (regression rate) and the efficiency of the burn. This is displayed in Figure 5 for well confined burns and shows that efficiency improves with faster burning rates at least to 3 mm/min.

Brash ice decreases the burning efficiency by impeding the wind herding. The herded areas are larger in Test 3 with 4.5 m/s winds than in ice-free Test 9 with winds of 2.5 m/s. Although these tests are not strictly comparable because the oils were not aged in the same way, they are similar within the accuracy of the experiment. In both Tests 2 and 3, the efficiency is lower than in the similar non-brash ice Tests 5 and 9. Smith and Diaz (1985) in their experiments at the OHMSETT facility, observed a 79% burning efficiency for weathered Prudhoe Bay oil in 4 m/s winds and 75% to 84% ice cover. Their results were obtained with large regular blocks of ice, however, and it is difficult to see how this compares to our brash ice conditions.

Buist and Twardus (1985) report an 88% efficiency for a large scale, confined burn of fresh Prudhoe Bay oil in 0 - 2 m/s winds, a result similar to a number of the runs reported here. The field trials conducted in the Beaufort by Dome (1981), in which oil percolated from below the ice into melt pools, resulted in burning efficiencies of 18% to 77%. In some instances wind herding was an important factor and oil thicknesses of up to 5 cm were reported.

HEATING OF LEAD WATER

Temperature measurements of the water, ice, and air were taken at the 8 m mark as the flame spread down the lead. An example of these temperature profiles is shown in Figure 6. Probe numbers 4 and 6 were located in the oil and number 5 was 1 cm higher in the flame. Other probes were placed from 3 cm to 8 cm below the water level and show a temperature rise of up to 5°C as the flame front passed over. A two-dimensional computer model of heat conduction into the lead water was used to calculate water temperatures. These temperatures were lower than those measured with the probes, indicating that convection must also be an important process of heat transfer in the water. From typical water temperature rises and flame duration, an estimate of the total heat flux into the lead water can be made. For an 80% burn efficiency, the heat flux into the water represents about 5% of the total heat generated by the oil combustion.

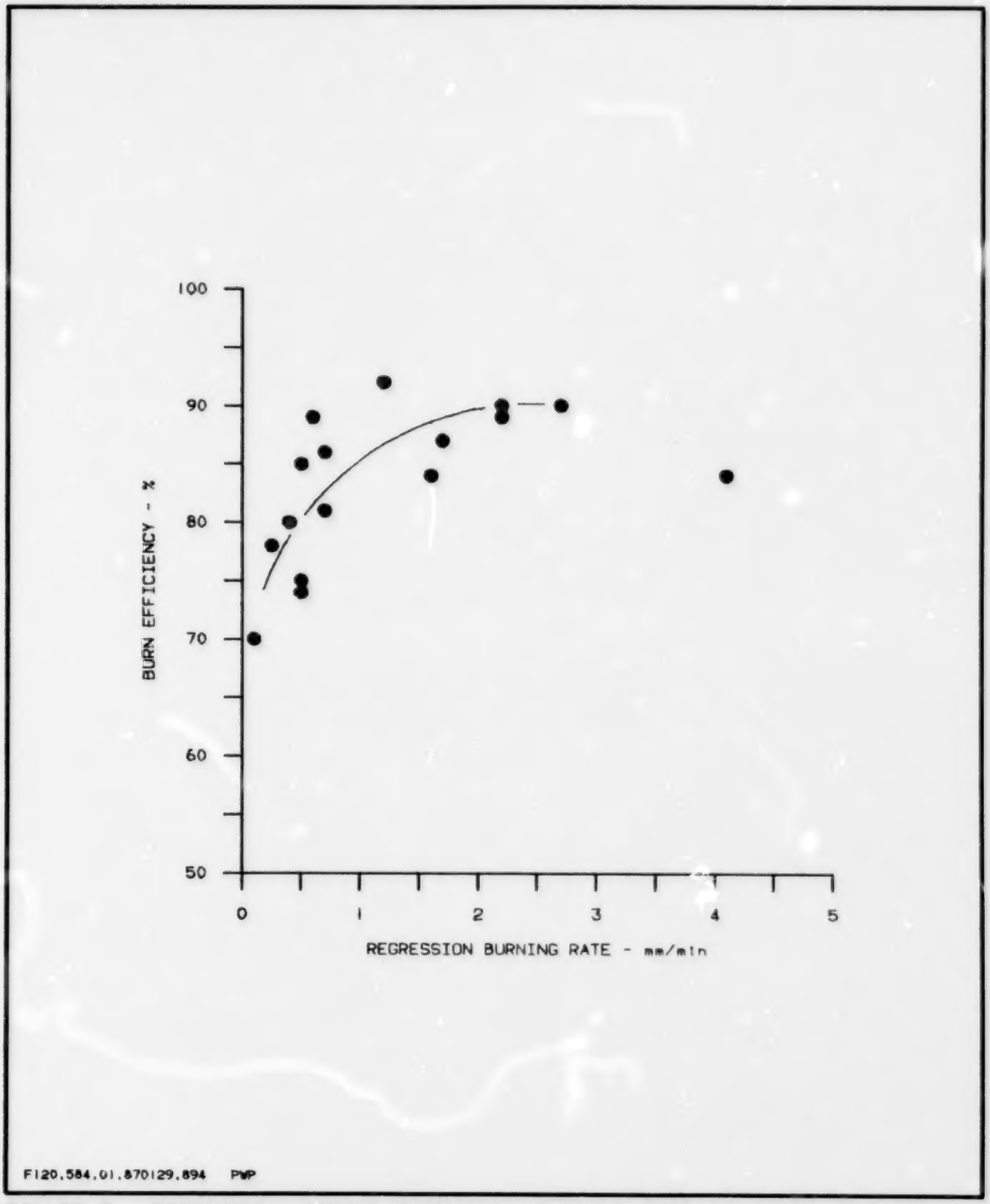

FIGURE 5. EFFICIENCY VERSUS REGRESSION BURNING RATE IN OIL 3 mm THICK.

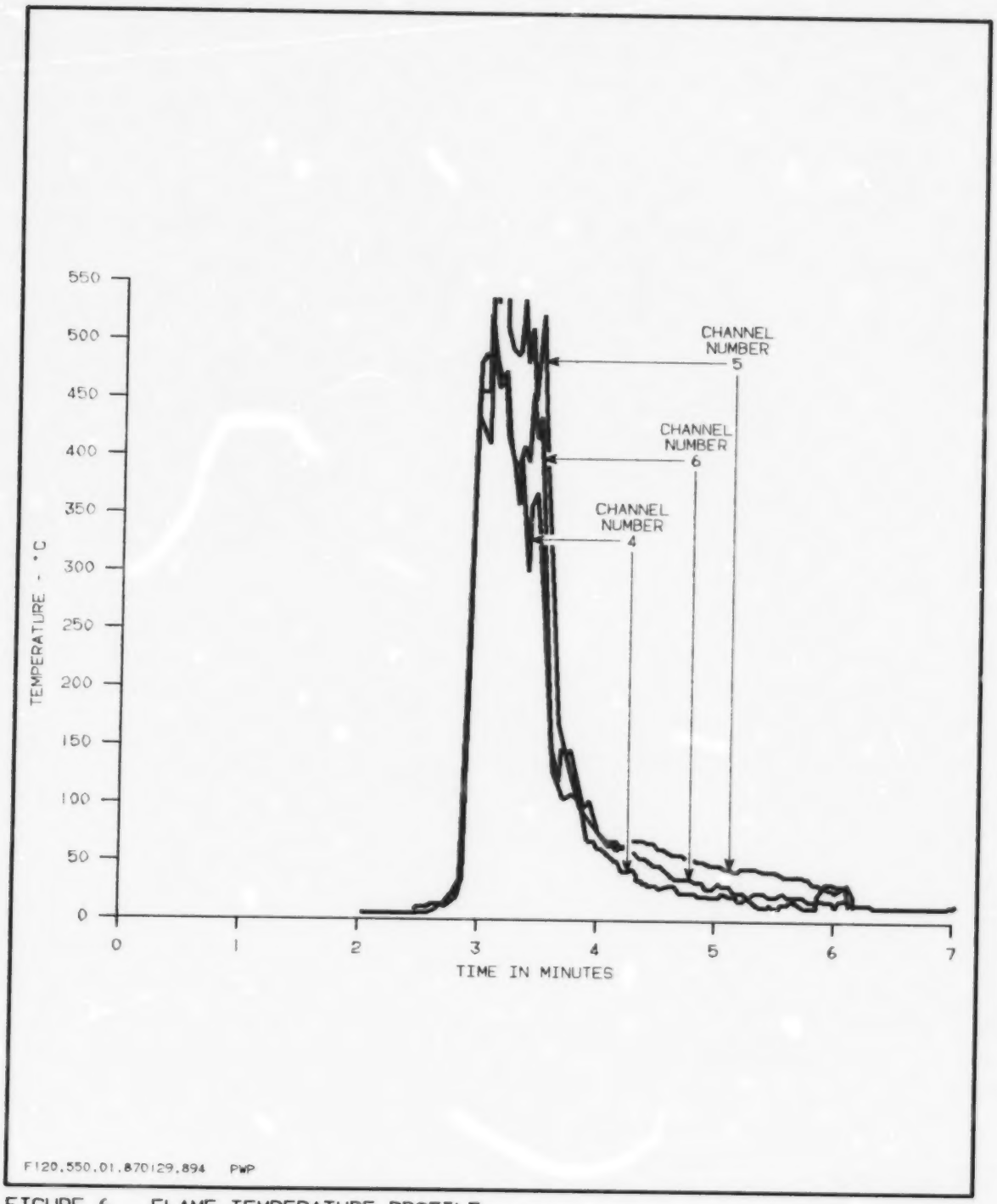

FIGURE 6. FLAME TEMPERATURE PROFILE

Temperature measurements of different parts of the flame were attempted using the infrared camera and video system. These were unsuccessful as the camera proved to be too sensitive for the high temperatures involved and no suitable neutral density filter could be found. Some priliminary image analysis of the colour video pictures indicate that these may be useful in determining the extent of different flame zones, but it is not clear what relationship these have to flame temperatures at this time.

RESIDUE ANALYSIS

In Table 2 the viscosities of the burn residues at 25°C and 38°C and the specific gravity at 15°C are listed. As expected, there is a general increase in these properties with increasing burning efficiency in the rectangular leads.

Figure 7 is a gas chromatogram of a typical burn residue which shows that almost no n-alkanes remain below C_{17}. While some waxes remain, the bulk of the material is made up of unresolved aromatics, heterogeneous nitrogen/sulphur/oxygen compounds (NSO's), and asphaltenes. A simulated distillation analysis gave the initial boiling point of the residue as 126°C (compared to 16°C for fresh Norman Wells oil) and showed that 48% of the residue remained unvolatilized at the maximum boiling point of 540°C. For comparison, Figure 8 is a gas chromatogram of unweathered Norman Wells crude oil.

A CHN analysis of a typical residue yielded:

C	85.96%	
H	11.64	H/C atomic ratio = 1.64
N	0.20	

This H/C atomic ratio is within the range observed for crude oils which implies that the burning process is not preferentially removing the hydrogen.

HYDROCARBONS IN THE WATER

Hydrocarbons were extracted from the upper 20 cm of the water column (with dichloromethane) before and after four of the tests. The total hydrocarbons added by the burning process ranged from 1.3 ppm to 1.7 ppm and averaged 1.5 ppm. Despite the vigorous surface agitation during the burn, it appears that not much oil or residue enters the water column. Figure 9 is a gas chromatogram of the extracted material which shows that there are very few compounds lighter than C_{15} and most consist of unresolved ring structures, NSO's, and asphaltenes, that is, probable burn residue material.

TABLE 2
Residue Analysis

Oil Weathering (%)	Test #	Specific Gravity at 15°C	Viscosity (CP) at 25°C	at 38°C
5	10	0.920	350	115
5	13	0.915	240	90
5	15	0.917	275	105
10	4	0.921	320	130
10	5	0.920	290	120
10	6	0.916	250	110
10	7	0.916	225	105
10	8	0.908	120	50
10	9	0.921	450	135
15	16	0.911	180	75
15	20	0.923	560	160
15	17	0.923	600	170
20	23	0.918	300	100
20	21	0.917	400	110
20	25	0.931	1425	310
~ 10	2	0.917	160	70
~ 10	3	0.931	635	250
5	24	0.911	160	65
5	22	0.914	310	80
5	11	0.904	100	45
5	12	0.911	160	65
5	14	0.918	365	130
15	18	0.920	525	150
15	19	0.917	245	105

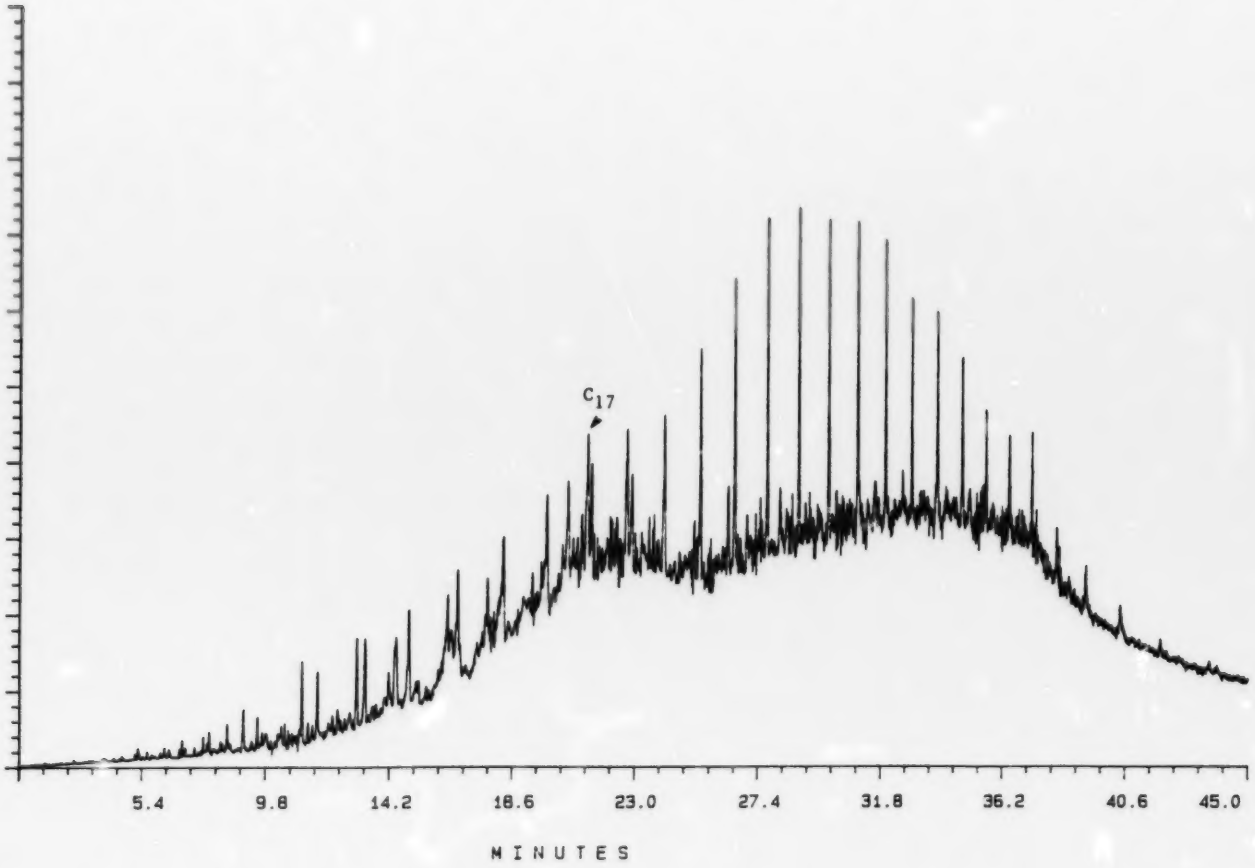

FIGURE 7. GAS CHROMATOGRAM OF TYPICAL BURN RESIDUE.

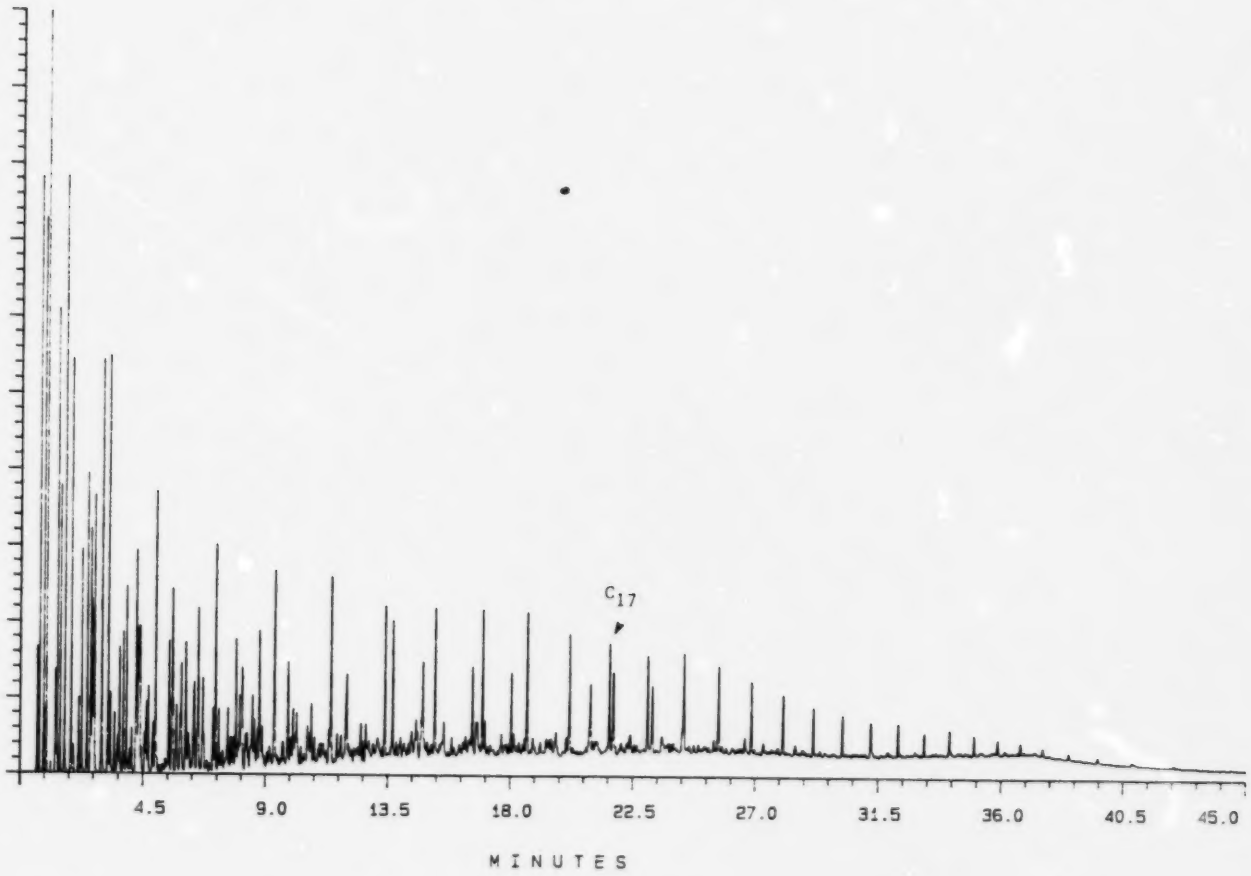

FIGURE 8. GAS CHROMATOGRAM OF FRESH NORMAN WELLS OIL.

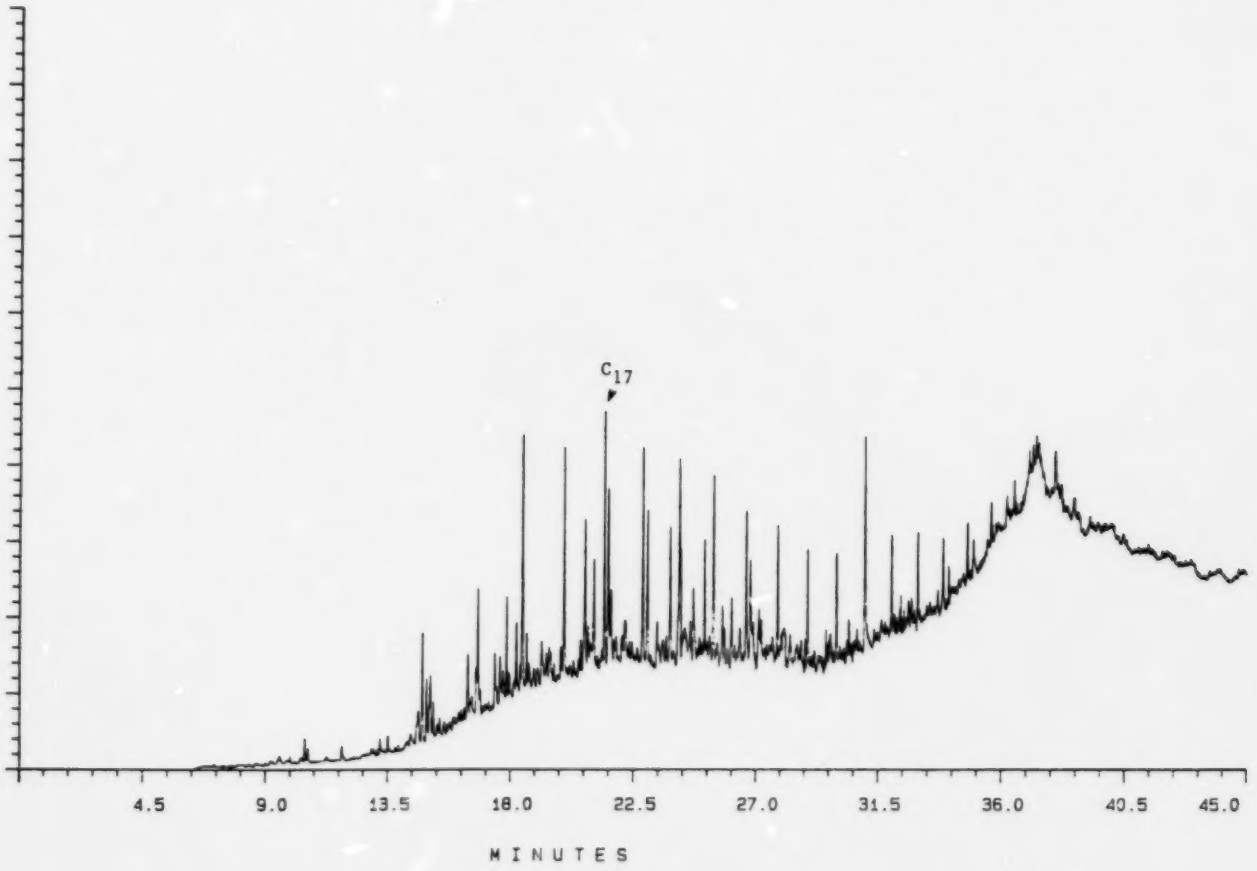

FIGURE 9. GAS CHROMATOGRAM OF HYDROCARBONS IN LEAD WATER.

EASE OF IGNITION

There did not appear to be a simple method of measuring the ease of ignition. A hand-held propane torch with a 6-cm diameter by 15-cm long flame proved best for igniting the burns. As the torch flame was touched to the oil slick, the time was measured until the flame became attached to the oil. These measurements were very inconsistent however, and appeared to be affected by small local winds. The time from first oil ignition until a stable flame front developed (arbitrarly taken to be when the flames covered 1 m^2) was also measured. These results are shown below for rectangular leads. Although there appears to be some dependance on wind as might be expected, there is no dependance on oil type in calm conditions. The problem of ignition requires further study, possibly as a laboratory experiment.

TEST	TIME	WIND m/s	WEATHERING %
10	0:44	0	5
13	0:42	1	5
15	0:17	2.5	5
5	1:50	0	10
4	0:45	2	10
9	0:36	2.5	10
16	1:15	0	15
20	1:09	1.4	15
17	0:42	2.5	15
21	0:40	1.4	20
25	1:00	5.8	20

SUMMARY OF PARAMETERS STUDIED

A summary of all the parameters studied with the range of values of each is presented in Table 3. Some comments are found there on the burning process at the extreme limits of each parameter. These usually indicate why experiments were not conducted beyond the stated limits or mention measurement problems which occurred within the ranges.

TABLE 3
Range of Experimental Parameters

Parameter Studied	Range	Comments on Range Limits
Oil thickness	0.1 - 0.4 cm	- Oil non-contiguous below 0.1 cm at 0°C - above 0.4 cm burning efficiency and flame velocity may be independent of thickness
Wind speed	0 - 6 m/s surface speed	- speeds up to approximately 12 m/s (or 40 km/h) equivalent meteorological winds - ignition very difficult above 5 m/s - oil herded to near top edge of lead at 6 m/s
Weathering	5 - 20%	- fresh Norman Wells crude too volatile for flame velocity measurements - could not readily parge oil to >20%
Lead geometry	unconfined oil to oil wind-herded into 14° angle	- some oil not burned when slick unconfined - good burning efficiency when oil herded into leads with angle as small as 14°
Ice thickness	3 - 10 cm above water level	- ice edge height had no effect on wind velocity down lead length - 3 cm height prevented herding with cross-wind of 4 m/s - winds greater than ~ 5 m/s began to herd oil over 3-cm freeboard
Brash ice	no ice to intimate oil/ brash-ice mix	- no method of characterizing brash ice density - brash ice covering <50% of water surface was melted during one burn

CONCLUSIONS

Wind herding, flame spreading rate, regression burning rate, and burning efficiency have been determined to characterize the burning of oil in ice leads. These measurements indicate that burning may be a suitable spill cleanup technique for remote cold environments such as the Beaufort Sea. Burning efficiencies of about 90% are obtained where oil can be confined by ice leads or wind herding so that oil thicknesses are 3 mm or thicker. Typical Beaufort winds are ideal for herding to these thicknesses. Oil weathering does not appear to affect burning efficiencies but brash ice impedes wind herding and lowers efficiencies. Where good wind herding occurs the point of oil ignition does not appear to be important. The residue from an efficient burn is very viscous at 0°C and can be easily removed from the water mechanically. Hydrogen to Carbon ratios of the residue are similar to some oils. Very little contamination of the water column was observed as a result of the burning process.

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